ESTCP Cost and Performance Report

(ER-0635)

USING ELECTRICAL RESISTIVITY IMAGING TO EVALUATE PERMANGANATE PERFORMANCE DURING AN IN SITU TREATMENT OF A RDX-CONTAMINATED AQUIFER

January 2009

ENVIRONMENTAL SECURITY
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **JAN 2009**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**

4. TITLE AND SUBTITLE
Using Electrical Resistivity Imaging To Evaluate Permanganate Performance During An In Situ Treatment Of A Rdxcontaminated Aquifer

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Environmental Security Technology Certification Program (ESTCP)

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR’S ACRONYM(S)

11. SPONSOR/MONITOR’S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
The original document contains color images.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**SAR**	**49**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

COST & PERFORMANCE REPORT
ESTCP Project: ER-0635

TABLE OF CONTENTS

Page

TABLE OF CONTENTS (continued)

Page

LIST OF FIGURES

Page

LIST OF TABLES

ACRONYMS AND ABBREVIATIONS

ASTM	American Society for Testing and Materials
ATSDR	Agency for Toxic Substances and Disease Registry
BAZE	biologically active zone enhancement
bgs	below ground surface
BTC	breakthrough curves
DNT	2,6-dinitrotoluene
DoD	U.S. Department of Defense
DPT	direct-push technology
ERI	electrical resistivity imaging
ESTCP	Environmental Security Technology Certification Program
EW	extraction well
GAC	granular activated carbon
gpm	gallons per minute
HA	health advisory
HAZWOPER	hazardous waste operations and emergency response
HE	high explosives
HMX	oxtahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine
ISCO	in situ chemical oxidation
IW	injection well
LC/MS	liquid chromatography/mass spectrometry
LLC	limited-liability corporation
MW	monitoring well
NAPL	Non-aqueuous phase liquid
NOP	Nebraska Ordnance Plant (former)
ORP	oxidation reduction potential
OSU	Oklahoma State University
PI	principal investigator
ppb	parts per billion
PPE	personal protective equipment
QA	quality assurance
QAPP	Quality Assurance Project Plan

ACRONYMS AND ABBREVIATIONS (continued)

QC	quality control
RDX	royal demolition explosive (hexahydro-1,3-5-trinitro-1,3,5-triazine)
RMS	root mean square
SARA	Superfund Amendments and Reauthorization Act
SEC	soil electrical conductivity
SOD	soil oxidant demand
SOP	standard operating procedures
TCE	Trichloroethene
TNB	1,2-dichloropropane, 1,3,5-trinitrobenzene
TNT	2,4,6-Trinitrotoluene
μg	microgram ($1x10^{-9}$)
UNL	University of Nebraska-Lincoln
USACE	United States Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency

ACKNOWLEDGEMENTS

We acknowledge the hard work and dedication of the students and staff from University of Nebraska-Lincoln (UNL) and Oklahoma State University (OSU) who contributed to the field work and data generation. These include Jeff Albano, Sathaporn Onanong, Chanat Chokejaroenrat, Greg Federko, Chris Mace, Robert Meyer, Kathleen Thompson, and Tim Sickbert. Dr. Todd Halihan of OSU has an ownership interest in Aestus, LLC, which has licensed the technology reported in this document.

This page left blank intentionally.

1.0 EXECUTIVE SUMMARY

1.1 BACKGROUND

The former Nebraska Ordnance Plant (NOP) in Mead, NE, was a military loading and packing facility that produced bombs, boosters, and shells during World War II and the Korean War. When at full capacity, the NOP occupied approximately 17,250 acres and consisted of four load lines, a bomb booster assembly plant, an ammonium nitrate plant, two explosive burning areas, a proving range, a landfill, and a wastewater treatment plant (U.S. Army Corps of Engineers [USACE], 2007). Ordnances were routinely loaded with the high explosives hexahydro-1,3,5-trinitro-1,3,5-triazine (RDX) and 2,4,6-trinitrotoluene (TNT). To limit chemical exposure to NOP employees during manufacturing, buildings were routinely rinsed with water which was eventually discharged into drainage ditches and sumps. These ditches became grossly contaminated with TNT and RDX, with soil concentrations exceeding 5,000 mg kg-1 near the soil surface (Hundal et al., 1997). When rainfall exceeded infiltration rates, ponded water that formed in the drainage ditches literally became saturated with munitions residues (i.e., reached high explosives [HE] solubility limits) before percolating through the profile. As a result, groundwater beneath the NOP is contaminated with several compounds used during ordnance production such as: TNT, 2,4- and 2,6-dinitrotoluene (DNT), RDX, octahydro-1,3,5,7-tetranitro-1,3,5,7-tetrazocine (HMX), trichloroethene (TCE), 1,2-dichloropropane, 1,3,5-trinitrobenzene (TNB), and methylene chloride.

Although several contaminants have been detected in the NOP groundwater, RDX and TCE comprise the majority of the plume (Woodward-Clyde, 1995). RDX was used in a variety of ordnances while TCE was used as a degreaser to clean pipelines carrying liquid oxygen fuel for missiles production. The size of the contaminant plume beneath the NOP is estimated at approximately 23 billion gallons (Woodward-Clyde, 1995).

To prevent the contaminated plume from migrating offsite and in the direction of municipal well fields, an elaborate series of 11 extraction wells and piping networks were constructed to hydraulically contain the leading edge of the RDX/TCE plume. Currently this $33 million dollar facility treats approximately 4 million gallons of groundwater per day via filtration through granular activated carbon (GAC). Annual operating costs are approximately $800,000/year. Current estimates indicate that relying solely on pump and treat will take more than 125 years to remove the RDX/TCE plume.

This project dovetails with an EPA-funded project (*Field scale Demonstrations of Innovative Remediation Technologies for Contaminated Soil and Water*, S. D. Comfort, granted 2005) designed to assess the efficacy of in situ chemical oxidation (ISCO) using permanganate to remediate RDX contamination. The ESTCP-funded project was undertaken in a cooperative, combined effort to demonstrate the utility of electrical resistivity imaging (ERI) as a geophysical tool to characterize the effects of the ISCO remediation effort. This cost report focuses primarily, but not exclusively, on the ESTCP-funded ERI demonstration (i.e., Costs of ERI).

ERI is a method of modeling subsurface electrical resistivity. In the context of ISCO, ERI economically acquires large numbers of spatially extensive data to track the distribution and flow of injectate. Contrasts in electrical resistivity in the subsurface provide specific targets for

further investigation and remediation. This in turn could minimize over-application of the injectate and avoid untreated zones in the contaminated plume.

1.2 OBJECTIVES OF THE DEMONSTRATION

The performance objectives of the U.S. Environmental Protection Agency (USEPA)-funded ISCO project were to demonstrate that permanganate could be used in situ to reduce RDX below health advisory levels. The performance objectives of the ESTCP-funded project were to observe the temporal distribution of the injected permanganate using ERI. The ISCO demonstration quickly reduced RDX levels by 80% but did not achieve health advisory levels within the time frame of the demonstration. ERI showed that the injectate followed preferential flow paths and descended rapidly outside the anticipated range of the demonstration and beyond the monitoring well network.

1.3 REGULATORY DRIVERS

The USEPA determined that contaminants from this site may present a threat to local residents and the Agency for Toxic Substances and Disease Registry (ATSDR) determined that the NOP is a public health hazard. Further, the Superfund Amendments and Reauthorization Act (SARA) specifies a preference for permanent solutions and innovative technologies (42USC9660, b).

1.4 DEMONSTRATION RESULTS

RDX concentrations temporally decreased in wells closest to injection wells IW-1 and IW-2 (Figure 4) as the permanganate migrated downgradient. We observed RDX degradation rates of 0.12/d in monitoring well (MW)-12 and 0.087/d in MW-14. These rates were lower than that observed under batch conditions at 11.5ºC (0.20/d) and likely a result of a lower initial permanganate concentration being established under field conditions (6,000 versus 15,000 mg/L). RDX concentrations decreased nearly 80% (from 64.6 to 13.1 µg/L) in MW-12, 70% in MW-14 (from 54.3 to 16.2 µg/L), 73% in MW-15 (from 87.3 to 23.5 µg/L), and 75% (from over 45 to 11 µg/L) in MW-16 before permanganate breakthrough was complete. We observed a slight decrease in RDX in MW-17 and MW-4. The permanganate concentrations sampled in MW-17 and MW-4 did not show a true breakthrough, which corresponds to the scattering RDX concentrations measure in both wells.

ERI data qualitatively showed that demonstration site heterogeneities forced injectate flow in unanticipated directions downward and along preferential flow paths. The fifteen monitoring wells and five additional boreholes showed that the injectate plume behaved unexpectedly but provided no further information describing the plume's behavior: ERI data quantitatively correlated to small-scale hydraulic conductivity data. ERI data also provided a quantitative correlation between permanganate concentration and resisitivity values, but the values were not directly monitored as changes through the injection period. The correlation only confirmed that the ERI provided quantitative data regarding the hydraulic structure of the aquifer. There was insufficient data from ERI and wells to obtain a quantitative correlation between changes in electrical resistivity and the concentration of injectate. This was due to the unexpected distribution of injectate during the experiment.

ERI data does not provide a direct substitution for well or direct push sample data. In its approach to site characterization, ERI can provide a role similar to medical uses of scanning technologies such as X-rays or CAT scans. During this experiment it guided direct push sampling to evaluate areas beneath the monitoring wells and found high concentrations of permanganate at depth. This technology is not a standalone characterization method as it only provides the distribution of electrical properties in the subsurface. However, to provide equivalent data, 112 boreholes per image would be required. ERI can be used to fill in data between boreholes or direct push locations, thus improving the conceptual model and decreasing the number of borings required. Additional work will be required to effectively apply the technology to injection protocols.

1.5 STAKEHOLDER/END-USER ISSUES

Despite problems encountered in getting the permanganate curtain uniformly distributed and throughout the well screen interval, the observed RDX destruction rates from this pilot-scale demonstration provide proof-of-concept that permanganate can degrade RDX in situ and support permanganate as a possible remedial treatment for the RDX-contaminated groundwater.

These efforts also demonstrated that ERI provides valuable information about the fate of injectate. In providing data on the location of the injectate flow, ERI data potentially prevented numerous random, expensive, and unnecessary attempts to locate the injectate by drilling or direct-push point sampling. These achievements address the Department of Defense's (DoD) need for scientific information regarding the real-world application of alternative technologies. The difficulties encountered also demonstrated the need to integrate monitoring strategies at all stages of the remediation design process.

This page left blank intentionally.

2.0 TECHNOLOGY DESCRIPTION

2.1 ELECTRICAL RESISTIVITY IMAGING (ERI) DEVELOPMENT AND APPLICATION

Electrical resistivity measurements have been used since the 1830s to interpret subsurface geology (Van Nostrand and Cook, 1966). The technique introduces current into the ground and measures the resulting potential field. An ERI image is an inverse model of the data: that is, it shows a synthetic distribution of resistivity that predicts values measured in the field. ERI is a generic term for the results from any arrangement of electrodes.

The Halihan/Fenstemaker technology is based on conventional electrical resistivity imaging techniques. Oklahoma State University's (OSU) proprietary data collection algorithms and software achieve more comprehensive data collection, higher data quality, and increased image resolution relative to other researchers using similar equipment (Halihan and Fenstemaker, 2004) (Figure 1). In most cases, Halihan/Fenstemaker technology increases resolution by approximately one order of magnitude. The Halihan/Fenstemaker technology is capable of semi-quantitative analysis of gasoline in the subsurface (Halihan et al., 2005). Nyquist et al. (1999) provided proof-of-concept for permanganate detection using standard ERI techniques by measuring a twenty-fold increase in electrical conductivity following injection of a 1% potassium permanganate solution.

2.1.1 Systems to Which the Technology Is Applicable

ERI technology as described here potentially adds value to any relatively shallow (up to a few hundred meters) subsurface investigation. Many features of interest occur within the top few hundred meters of Earth's surface, and ERI techniques may economically provide valuable information on these. Most obvious are hydrogeological and environmental applications: ERI is particularly well-suited to detecting variations in water saturation, non-aqueous phase liquid (NAPL) saturation, distribution of lithology, and saltwater intrusion. ERI techniques can also potentially provide information for geological engineering, such as the depth and attitude of geological contacts and faults, location of potential sinkholes in karsted carbonates, and slip surfaces underlying wasting masses.

2.1.2 Target Contaminants

ERI can provide information for any material or feature that has electrical resistivity values contrasting with background material. For example, ERI is particularly useful in identifying fresh NAPLs (high resistivity) or saline water (low resistivity) against a background of typical groundwater. Also, as in this case, ERI can identify the flow paths and relative concentrations of remedial injectates so long as the amendment creates a concentration-dependent contrast in subsurface electrical resistivity.

2.1.3 Theory of Operation

An ERI datum is collected by inducing a current between two points and measuring the electrical potential between two other nearby points. Applying Ohm's Law gives the resistance between

points. A computer connected by cable to a series of electrodes on or in the ground very quickly and efficiently collects large datasets.

With a dataset of hundreds of resistance measurements acquired along a line at the surface, it is possible to mathematically create a model of the distribution of material resistivity on the plane below the acquisition line. This process, called inverse modeling, iteratively solves a system of equations to create an areal distribution of model resistivities that, if measured, would closely match the resistance measured in the field.

2.2 PROCESS DESCRIPTION

Most generally, ISCO injects a chemical oxidant into contaminated media. In this demonstration, contaminated groundwater was extracted from a central well, mixed with sodium permanganate, and injected into two peripheral wells for approximately 7 hours. This type of recirculating system increases the volume of contaminated medium treated while minimizing the net volume extracted or injected. Oxidant concentrations, well-distribution, and flow rates can all be adjusted to meet site-specific requirements. Monitoring ISCO requires the same sample collection and analysis as other remediation methods.

As performed at the former NOP, an ERI survey requires installing 56 steel stakes into the ground to establish electrical contact, attaching a cable to the electrodes, and initiating a data collection protocol on the controlling computer. A single data collection event requires from about one-half to 2 hours, depending on the data collection protocol. Executing the inverse modeling software to develop the model image requires one-half to 2 hours of operator time for each data set collected.

2.2.1 Mobilization, Installation, and Operational Requirements

ISCO as demonstrated here requires extraction and injection wells appropriate to the scale, scope, and hydrogeologic context of the contamination. Directly monitoring the process requires additional wells or boreholes. Well construction is the largest capital expense, followed by the injection system and utilities. Long-term operation would require occasional maintenance of pumps, tanks, and wells. Permanganate and pump operation and maintenance are the largest operational expenses.

This demonstrated design could be implemented on the scale of the former NOP using more, possibly larger, extraction and injection wells operated over a period of many months to several years. Other ISCO designs such as low-flow injection-extraction, continuous injection-only, and direct push could be explored (Figure 1).

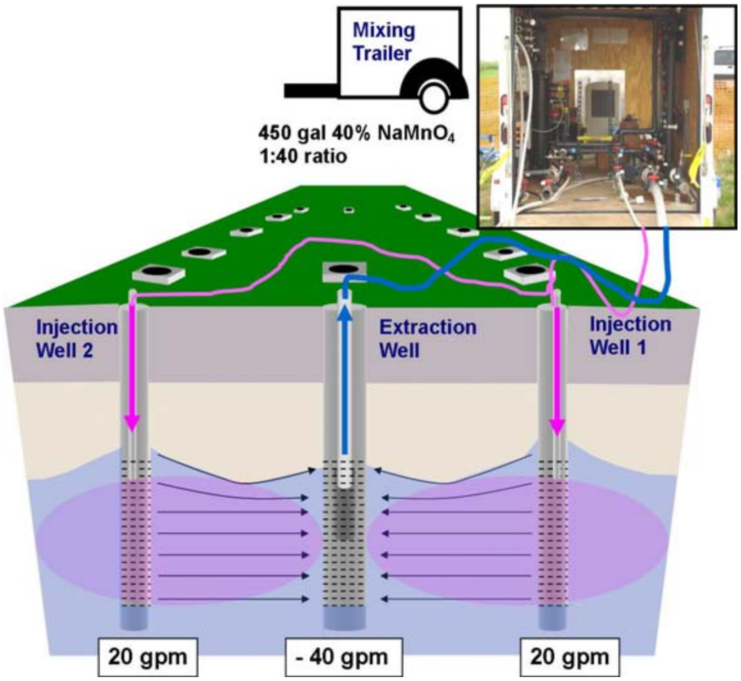

Figure 1. Schematic of injection setup showing photo of Aquifer Solutions, Inc. trailer.

ERI requires acquisition equipment, including electrode stakes, cables, and a control and data collection computer. An experienced three-person team can install and uninstall the ERI equipment. Once lines are in place, a single person can monitor the equipment and collect data. The system can also be operated remotely in higher risk environments and for short- or long-term transient monitoring.

Processing of ERI data requires inversion software and the location in space of the electrodes. For two-dimensional surveys, this requires a survey of the relative elevation of the electrodes; for three-dimensional data, the lateral dimensions are required as well. If required, a range of visualization options are available to place the data in three dimensional images.

2.2.2 Key Design Criteria

ISCO requires a physical environment that allows the chemical oxidant to mix with the contaminated medium and a chemical environment in which the oxidant will preferentially react with the contaminant. Extreme physical heterogeneity and/or strongly preferential flow paths can prevent adequate mixing of the oxidant and the contaminant. A chemical environment with a high oxygen demand, (e.g., high organic matter) or strongly reducing environment will compete with the contaminant for the oxidant.

ERI requires an electrical resistivity environment that is sufficiently homogeneous and a material of interest, e.g., permanganate, with an electrical resistivity that contrasts with the environmental background. The former NOP is a challenging, yet suitable site: the background electrical resistivity is not homogenous, but the distribution is geologically sensible. Permanganate is less resistive than the aquifer material and groundwater, and thus contrasts with background. The collection of pre-injection background ERI data proved critical to understanding injectate flow.

2.2.3 Performance

The ISCO demonstration quickly and significantly reduced groundwater RDX concentrations by up to 80% (64.6 to 13.1 μg/L) but did not achieve reduction to target levels (2 μg/L) during the demonstration period in the available monitoring well network. ERI successfully observed the appearance and movement of the injectate; however, ERI required more intense processing and analysis to track the injectate. Also, because heterogeneities forced injectate to flow away from monitoring wells, analyses were unable to quantify injectate concentrations.

2.2.4 Personnel/Training Requirements

ERI requires one trained operator, and two additional people to efficiently install electrodes and connect cables. Additional efficiency can sometimes be gained by having a fourth person available to survey elevations and assist with electrodes and cables. An individual can be trained to operate ERI equipment with about 4 hours of instruction and active participation in three or four ERI surveys.

2.2.5 Ease of Operation

ERI installation and data collection requires moving a total of less than 250 pounds (115 kg) of equipment including console, stakes, cables, and batteries, with no package exceeding 70 pounds (32 kg). Additional equipment for traffic control, drilling through pavement, or surveying can significantly increase the amount of equipment mobilized to a site. Executing a data collection protocol requires a short sequence of directed keystrokes at the console.

2.3 PREVIOUS TESTING OF THE TECHNOLOGY (ERI)

The Halihan/Fenstemaker ERI technique successfully mapped geology, located zones of increased groundwater flow, and located subsurface environmental impacts, leaking pipelines, buried tanks, and landfill and burial pit boundaries. OSU has also conducted transient research observing a heap leach pit undergoing wetting over time and injection of phosphorous for groundwater research (Webb et al., in press; Sima et al., 2008).

Aestus, LLC has used ERI for several years in the United States and internationally. The ERI images have been confirmed through fluid or soil sampling to be a true representation of subsurface conditions. The technique has been applied at approximately 60 sites to date.

Common geophysical techniques are limited by several factors, as outlined by Stollar and Roux (1975). They noted a concurrent loss in signal quality and resolution with increasing depth. They also note that there must be a significant contrast between the contaminated and uncontaminated groundwater for resistivity surveys to be effective tools. Although the costs of resistivity techniques may be lower than point monitoring methods (i.e., wells), for long-term projects, the results are often difficult to correlate with objectives and still require traditional groundwater sampling techniques. These problems are exacerbated by a lack of integration among geophysicists, hydrogeologists, and microbiologists. A major problem with the application of electrical techniques to contaminant detection is that many contaminants of interest to site managers, such as NAPLs (petroleum products usually), are electrical insulators. The ERI method works best for identifying conductors, making it difficult to image relatively

resistive NAPL. Dr. Halihan has minimized these problems by altering the methodologies used to acquire and process ERI data to create drillable images.

This page left blank intentionally.

3.0 DEMONSTRATION DESIGN

3.1 PERFORMANCE OBJECTIVES

The following are the evaluation points to be determined in the cooperative USEPA and Environmental Security Technology Certification Program (ESTCP) demonstrations:

- Validate treatability study predictions for technology performance as established by the University of Nebraska (UNL) and Oklahoma State University (OSU).
- Assess the performance of ISCO using permanganate to remediate RDX-contaminated groundwater and reach concentrations below the US EPA Health advisory level of 2 µg/L RDX.
- Assess the performance of ERI to identify spatially and temporally the permanganate plume injected into the RDX-contaminated groundwater.
- Quantify the cost of the ISCO process to remediate RDX-contaminated groundwater by:
    - o Determine capital costs associated with the implementation of the ISCO and ERI process.
    - o Determine the operation and maintenance costs associated with the ISCO/ERI process.
    - o Identify the site characteristics that affect treatment costs.

Table 1. Performance objectives.

Type of Performance Objective	Primary Performance Criteria	Expected Performance (Metric)	Actual Performance Objectives Met
Qualitative	Identify initial permanganate plume following injection	2-D image corresponds with well data	Yes
	Track temporal changes in permanganate plume's size and location	2-D image corresponds with downgradient monitoring well data	Mixed results
Quantitative	Reduce RDX mass	>90%	No
	Meet regulatory standard	<2 µg/L	No
	RMS* of ERI data sets	<20%	Yes

*root mean square

3.2 SELECTION OF TEST SITE

An ideal test site for demonstrating the ability of ERI to monitor an ISCO treatment would be both electrically and hydrogeologically homogenous. A test site should be contaminated either uniformly throughout the domain of the test, or with a clearly identifiable plume. A site should be large enough to accommodate a demonstration without affecting local water users. Also, existing infrastructure would reduce costs of conducting the demonstration.

Based on the regional geology (Condra and Reed, 1943; Piskin, 1971), the materials at the former NOP were reasonably homogenous. The test site is located in an existing large, contained, well-characterized contaminant plume. Injection, extraction, and monitoring wells had been constructed for a previous study (biologically active zone enhancement [BAZE]). The local groundwater gradient is consistent with the regional regime. The size of the demonstration is small relative to the contaminated area at the former NOP, and a downgradient containment system was operating, reducing any risk to groundwater users. Conducting the ISCO/ERI demonstration at the site of a previous BAZE experiment supports direct comparison of technologies.

3.3 TEST SITE/FACILITY HISTORY/CHARACTERISTICS

The former NOP was a military loading, assembling, and packing facility that produced bombs, boosters, and shells during World War II and the Korean War. Ordnance was loaded with TNT, amatol (TNT and NH_4NO_3), tritional (TNT and Al), and Composition B (~60% RDX and 40% TNT). TCE was used as a degreaser at the site. During and following ordnance production, contaminated wastewater was discharged into sumps and drainage ditches, from which contaminants leached into the soil and groundwater. Groundwater underneath and downgradient from the site has RDX concentrations as high as 534 μg/L and TCE concentrations as high as 4800 μg/L.

3.3.1 General Hydrogeology

The former NOP is entirely within the Todd Valley, located near the western edge of the Dissected Till Plains section of the Central Lowland physiographic province. The Todd Valley is an ancestral Platte River valley that has been filled with unconsolidated Pleistocene sediment, the Todd Valley Formation. At the demonstration site, approximately 6.1 m (20 ft) of Peoria Loess mantles the Todd Valley Formation, which is comprised of approximately 15.2 m (50 ft) of fine sand overlying approximately 13.7 m (45 ft) of coarse sand. Cretaceous Dakota Group sandstones and shales serve as a lower confining unit. The Todd Valley aquifer and the Platte River alluvial aquifer behave as a single system. The regional water table slopes southeast with an average gradient of 2.27 m/km (0.0023, or 12 ft/mile) (Woodward-Clyde, 1995). Depth to groundwater ranges from 11.6 m (38 ft) to 15.24 m (50 ft) (Woodward-Clyde, 1995).

3.3.2 Demonstration Site Hydrogeology

Soil cores and downhole soil electrical conductivity (SEC) data indicate roughly 5.5 m (18 ft) of Peoria Loess above at least 16.2 m (53 ft) of medium to fine sand (maximum soil core depth was 22.3 m (75 ft) below ground surface). Average well horizontal hydraulic conductivity values (K_h) range from 4 m/day to 20 m/day (Figure 2). These values are consistent with average hydraulic conductivity of the upper fine sand layer previously reported at 15 m/day by the Army Corps of Engineers (Woodward-Clyde, 1995). Whole-screen and packer slug tests show significant horizontal and vertical variations in hydraulic conductivity (Figure 3).

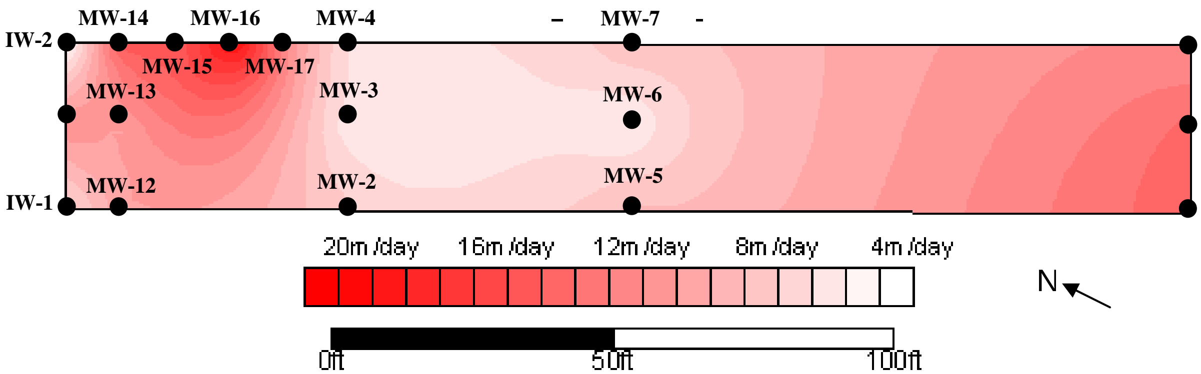

Figure 2. Hydraulic conductivities within the study area.

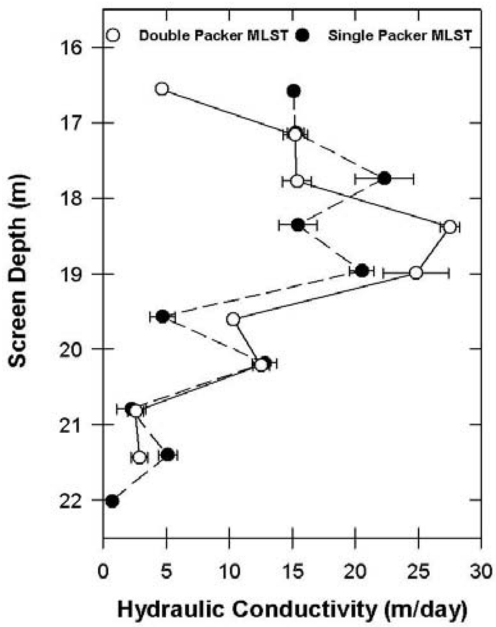

Figure 3. Hydraulic conductivity K_h observed in MW-15 using single- and double-packer multilevel slug test configurations.

Figure 3 indicates slightly lower values of K_h from single-packer tests than from double-packer tests, and clearly shows a preferential flow zone at depth (17.5-19 m) (58-63 ft). The packer tests indicate that preferential flow pathways are likely ubiquitous in this paleoalluvial environment.

3.4 PHYSICAL SETUP AND OPERATION

ISCO extraction, injection, and 11 monitoring wells were in place from the previous BAZE experiment. Additional monitoring wells, illustrated in Figure 4B, were installed in April, 2007. ERI installation consisted of installing metal stakes approximately 6 inches into the ground for each line and for each data collection event (May, June, July, and August, 2007). Traffic was controlled on the unpaved site road during this time with traffic cones. The site for the monitoring wells was mowed in limited areas to improve site access.

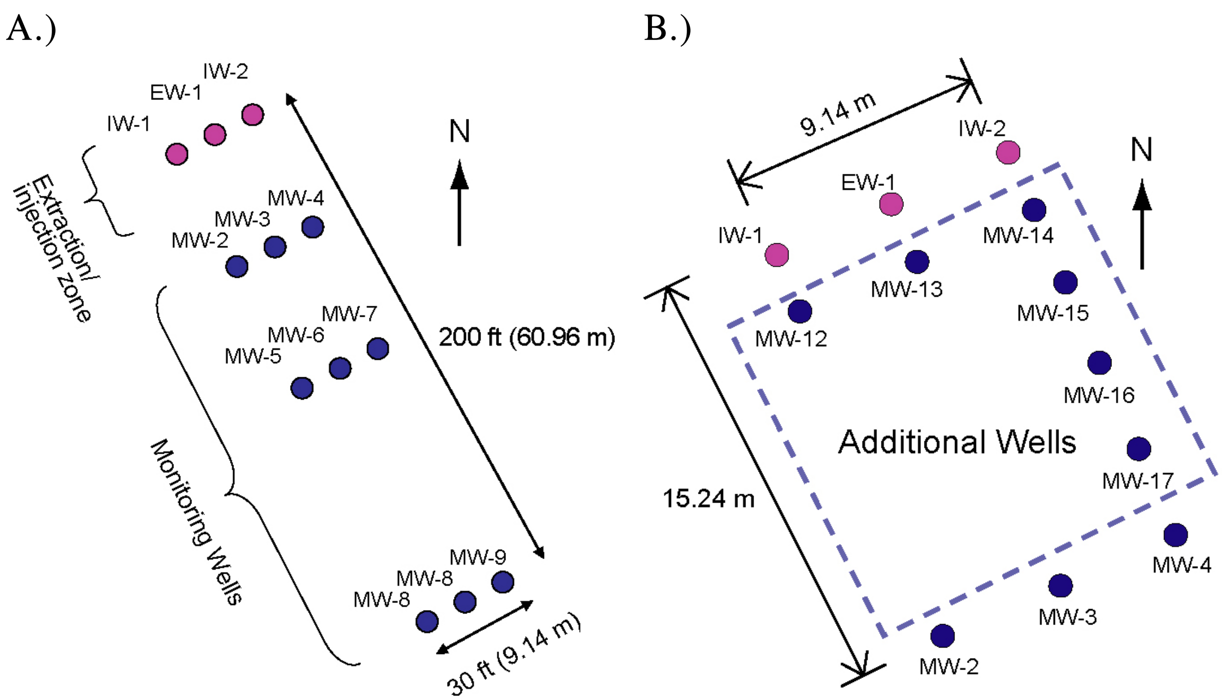

Figure 4. Schematic diagram showing (A) locations of original BAZE wells and (B) larger-scale schematic of extraction/injection zone and newly constructed wells MW-15, MW-16, and MW-17.

On June 18, 2007, Aquifer Solutions, Inc. established a safety fence around the injection site, installed a decontamination shower, and connected their injection trailer to the pumping and injection wells. Electrodes for two ERI lines (Line 2 and Line C) were placed over the well curtain area and perpendicular to the curtain orientation over the extraction well. The injection was performed on June 19, 2007, for 8 hours. Groundwater samples were collected and ERI data was collected continuously and repeatedly during and immediately following the injection until 25 hours after the injection began. After 25 hours, the ERI lines were moved to collect data along the remaining eight lines. Based on observations at the monitoring wells, data were collected along two additional lines (ERI lines 3 and 4). While the larger set of ERI data were being collected, the injection system was removed from the site.

During the period of July 20-22, 2007, a 12-line ERI dataset was collected from the site. At this point, the grassy areas that had been mowed had not grown significantly, but the soybean field was higher.

The final ERI sampling period occurred during August 29-31, 2007. The sampling evaluated 10 specific ERI lines and imaged 4 lines twice as deep to determine if injectate had moved vertically below the previous datasets, and to confirm whether the ERI technique could distinguish the injectate from the geological materials.

3.4.1 Injection Procedures

Groundwater was extracted from well extraction well (EW)-1, mixed with sodium permanganate, then gravity fed into each of two neighboring injection wells, IW-1 and IW-2, at

approximately 77.7 L/min (20.5 gpm) for about 400 minutes. Following the injection, extracted groundwater from EW-1 was recirculated to wells IW-1 and IW-2 for 42 minutes.

3.5 SAMPLING/MONITORING PROCEDURES

During injection, sodium permanganate concentrations were periodically measured with a portable spectrophotometer to monitor the concentration delivered to the injection wells and breakthrough at the extraction well. Specific conductivity was measured at the same times to establish a calibration curve to relate conductivity to sodium permanganate concentration.

Groundwater was monitored in selected wells approximately twice weekly (18 times) for the 59-day period from June 19 through August 17, 2007. Monitoring comprised purging three well volumes, collecting a groundwater sample from 21 m depth, and measuring electrical conductivity at 0.6 m intervals from 15.2 m to 23.2 m depth. Well selection was guided by anticipated flow direction and, for later sampling events, by historical appearance of permanganate in samples. Collected samples were analyzed for permanganate; selected samples were analyzed for RDX.

ERI surveys were conducted one month prior to, during, and one and two months following the injection. As planned, pre-injection, concurrent, and one-month post-injection surveys were along lines parallel and perpendicular to the regional groundwater gradient. Also as planned, multiple surveys were conducted during the injection along the line passing through the injection well-extraction well plane (Line 2), and perpendicular to that plane and passing through the extraction well (Line C) (Figures 3.5-4 and E1 of the Final Report). In addition to planned surveys, two-months post-injection, Lines C, D, and 6; and additional Line G were surveyed with 6 m spacing, twice the originally planned spacing, to explore greater depth for signs of the injectate. The ERI instrument was checked prior to each sampling interval for the functioning of data channels and relays, and tested for calibration.

3.6 ANALYTICAL PROCEDURES

3.6.1 Sample Analysis

All groundwater samples collected from monitoring and injection wells were analyzed using standard methods approved by USEPA or the American Society for Testing and Materials (ASTM). Ten percent of the total field samples were used for quality assurance (QA)/quality control (QC) for data completeness as well as accuracy. Instruments used for chemical analysis were calibrated daily from standards prepared from stock solutions and checked after every 10 samples to validate repeatability.

ERI data were analyzed with standardized protocols developed at Oklahoma State University (Halihan et al, 2005). There are no standard USEPA or ASTM standards for collection and analysis of ERI data. Data quality was assessed through repetitive and reciprocal measurements and evaluation of inversion RMS error. Appendices A, B, and C of the full report contain the Quality Assurance Project Plan (QAPP) and standard operating procedures (SOP) for laboratory and field sampling, which were developed for the ISCO demonstration at the NOP.

3.6.2 Experimental Controls

Baseline data for the ISCO (contaminant concentration) and ERI (electrical resistivity) demonstration were collected prior to permanganate injection. A dedicated monitoring well (MW-00) upstream of the injection wells provided the RDX concentration flowing into the demonstration area. Background ERI data collected during May 2007 provided electrical conditions that existed prior to the injection.

4.0 PERFORMANCE ASSESSMENT

4.1 PERFORMANCE DATA (NARRATIVE)

Based on our modeling efforts of the extraction-injection well configuration and assuming piston-type flow (i.e., no dispersion), approximately 7 h of pumping (extraction-injection) would have been needed to complete the permanganate curtain. Initial permanganate breakthrough at the extraction well, however, was observed within 77 min. Once all the permanganate had been injected into IW-1 and IW-2 (t ~ 7 h), the sodium permanganate concentration in EW-1 had only reached 2386 mg/L, indicating that a uniform curtain of permanganate was not established across the injection wells.

ERI results indicated that only differencing between pre-injection and immediately post-injection showed any discernable changes. The majority of these changes were observed on lines placed over the injection wells (IW-1, IW-2) and perpendicular to the injection plane. At these locations, both positive and negative changes occurred. The changes ranged from -13% to 13%. Although these changes were consistent with a conductive injectate being placed in the aquifer, the observed changes were much smaller than expected. The location of the changes indicates that significant changes occurred above the water table. The other change occurred upgradient of the injection wells and vertically below and to the southwest of the injection wells as shown by the composite ERI. These results signify that the permanganate followed some preferential flow paths that were not congruent with the location of the monitoring wells. ERI conducted during the injection process also indicated that our permanganate curtain failed to develop with the injection well locations having ERI signals approximately twice as high as the extraction well location.

Another contributing factor to the observed permanganate distribution was the observed head buildups in the injection wells during the permanganate injection. IW-1 had a maximum buildup of 3 m of permanganate while IW-2 was at 7 m (23 ft) near the end of the injection. IW-1 and IW-2 head differences were previously encountered during a 30 min pre-injection test using water but not to the extent observed during the permanganate injection. The differential head buildup observed between injection wells also likely contributed to a less than uniform distribution of permanganate.

RDX concentrations temporally decreased in wells closest to the injection wells (IW-1, IW-2, Figure 4) as the permanganate migrated down gradient. We observed RDX degradation rates of 0.12/d in MW-12 and 0.087/d in MW-14. These rates were lower than what was observed under batch conditions at 11.5ºC (0.20/d) and likely a result of a lower initial permanganate concentration (6,000 versus 15,000 mg/L). RDX concentrations decreased nearly 80% (from 64.6 to 13.1 µg/L) in MW-12, 70% in MW-14 (from 54.3 to 16.2 µg/L), 73% in MW-15 (from 87.3 to 23.5 µg/L), and 75% (from over 45 to 11 µg/L) in MW-16 before permanganate breakthrough was complete. We observed a slight decrease in RDX in MW-17 and MW-4. The permanganate concentrations sampled in MW-17 and MW-4 did not show a true breakthrough, which corresponds to the scattering RDX concentrations measure in both wells.

When permanganate and bromide breakthrough curves were normalized to the maximum concentrations observed, the MnO_4^-/Br^- breakthrough curves (BTC) in wells MW-12, MW-14,

and MW-15 were nearly identical and indicated that permanganate consumption by native soil oxidant demand (SOD) was minimal. Using an integration technique, we calculated permanganate consumption to be 0.25% to 0.76% for wells MW-12, MW-14, and MW-15, indicating low permanganate consumption after a linear distance of 6 m (20 ft). The low consumption of permanganate under in situ conditions is also supported by the fact that while multilevel sampling via direct push technology (DPT), permanganate concentrations >900 mg/L were observed 72 d after injection at a linear distance of >14.5 m from IW-2. The low oxidant demand of both aquifer and groundwater (i.e., RDX concentration) indicate that permanganate could potentially oxidize a large volume of RDX-contaminated groundwater within the Todd Valley aquifer.

Permanganate breakthrough was observed in all wells within the field site except MW-2 and MW-3. Electrical conductivity measurements conducted prior to groundwater sampling indicated that the permanganate plume did not uniformly enter the monitoring well screens but followed preferential flow paths found during multilevel slug testing of MW-15 prior to permanganate injection. Calculated hydraulic conductivities (K_h) for MW-15 range from 3 m/day to 27 m/day with highest conductive intervals between 18.9 m and 19.8 m below ground surface (bgs). Groundwater sampling conducted via DPT at 24, 56, and 72 days verified permanganate plume bifurcation, or plume fingering within the site. We believe that this bifurcation was due to preferential pathways caused by the depositional nature of the Todd Valley sands, which were deposited in a braided stream system similar to the current Platte River near Ashland, NE. The sedimentology of a braided stream is complex and encompasses several channels characterized by high width/depth ratios, steep slopes, and usually low sinuosities. Because of this stratification, monitoring wells only captured fingers of permanganate that was mixed with non-treated groundwater during pumping, thereby diluting permanganate/bromide concentrations within the well and artificially inflating RDX concentrations due to mixing within the well casing. Despite problems encountered in getting the permanganate curtain uniformly distributed and throughout the well screen interval, the observed RDX destruction rates from this pilot-scale demonstration provide proof-of-concept that permanganate can degrade RDX in situ and support permanganate as a possible remedial treatment for the RDX-contaminated groundwater.

Table 2. ISCO at the former NOP, Mead, NE

Performance Criteria	Primary or Secondary
Types of data collected	Groundwater, analyzed for RDX and permanganate
Sampling frequency	Groundwater collected immediately following, then approximately twice a week for 10 weeks post-injection
Quantity of groundwater treated	Theoretical minimum, approximately 70 m^3 of groundwater in a volume of 230 m^3 aquifer material, containing 4 g RDX
Untreated and treated contaminant concentrations	RDX mean concentrations: pre-treatment: ~45 to 87 µg/L post-treatment: ~23 to 11 µg/L
Cleanup objectives	Reduce RDX concentration below Health Advisory Level (2 µg/L)
Comparison with cleanup objectives	Compare to BAZE results (ESTCP Project ER-0110), when final report is available
Method of analyses	See appendices in Final Report
QA/QC	See appendices in Final Report
Other residues	Well cuttings and purge water were taken to treatment facilities
For additional information on the demonstration-scale project, refer to the Final Report	

Table 3. ERI at the former NOP, Mead, NE.

Performance Criteria	Primary or Secondary
Types of data collected	Groundwater, analyzed for RDX and permanganate electrical resistivity
Sampling frequency	Groundwater collected immediately following, then approximately twice a week for 10 weeks post-injection ERI collected during and immediately after injection, and after 5 and 10 weeks post-injection.
Quantity of groundwater treated	Theoretical minimum, approximately 70 m^3 of groundwater in a volume of 230 m^3 aquifer material, containing 4 g RDX
Untreated and treated contaminant concentrations	Groundwater was analyzed for RDX and $NaMnO_4$
Cleanup objectives	Site characterization method
Comparison with Cleanup objectives	Monitoring wells data
Method of Analyses	See appendices in Final Report
QA/QC	See appendices in Final Report
Other residues	None
For additional information on demonstration-scale project, refer to the Final Report	

Table 4. Process performance criteria.

Performance Criteria	Description	Primary or Secondary
Contaminant reduction	RDX by oxidation: 90% reduction	Primary
Contaminant mobility	ISCO does not directly affect RDX mobility. Permanganate reduction will precipitate MnO_2, potentially constricting pores and affecting hydraulic conductivity.	Primary Secondary
Hazardous materials	The demonstration injected $NaMnO_4$, an oxidizer. RDX, TCE, and SOD consume the permanganate, ultimately leaving common ions (Na^+, Cl^-, etc.).	Secondary
Process waste	None	N/A
Factors affecting technology performance	Aquifer chemistry: • SOD: chemically reduced material will consume permanganate • Temperature, pH, and ionic composition Flow rate and feed rate affected the size and time needed to establish a permanganate curtain of permanganate. ERI performance at NOP was controlled by the electrical contrast between the permanganate plume and the surrounding aquifer and injectate flow away from the anticipated path. It was anticipated that the injected permanganate mass would generate a strong conductive signature in the subsurface.	 Primary Secondary Primary Secondary
Reliability	ISCO: No failures occurred. ERI: One dataset was discarded due to battery voltage falling below specification.	Primary Primary

Table 4. Process performance criteria (continued).

Performance Criteria	Description	Primary or Secondary
Ease of use	ISCO required two to three people to perform the permanganate injection. Moderate level training was required for permanganate injection such as: hazardous waste operations and emergency response (HAZWOPER), operation of pumps, meters, and real-time measurements like pH and oxidation reduction potential (ORP) meters. ERI measurements required two individuals trained in ERI measurements and a third to help deploy and manage the equipment.	Primary Primary
Versatility	The ISCO technology does not have any specific boundaries of use. Provided groundwater can be reached by injection wells, any site containing explosive-contaminated groundwater can be treated. The ERI technology can generally reach a depth of up to 100 m. Typical line length for this project was 150 m (500 ft) to observe 30 m (100 ft) deep.	
Maintenance	ISCO equipment requires occasional pump and plumbing maintenance. ERI equipment requires battery charging, occasional cable maintenance, and system calibration.	Primary Primary
Scale-up constraints	ISCO can be scaled up by increasing the size, spacing, and number of wells. ERI theoretically can be scaled up to any size. Practically, cost increases if the application required surface lines longer than 200 m (650 ft), as the production rate decreases. Scaling up ERI also imposes tradeoffs between data collection costs and resolution.	Primary

4.2 PERFORMANCE CRITERIA

Table 5. Project performance confirmation.

Primary Criteria	Expected Performance Metric (pre demo)	Actual Performance
PRIMARY CRITERIA (Performance Objectives) (Qualitative)		
Contaminant mobility	ISCO/ERI does not have any influence on contaminant mobility.	No enhanced mobility observed
Faster remediation	A decrease in RDX concentration from ~70 µg/L to <2 µg/L, which is the health advisory (HA) for RDX.	HA level (<2 µg/L)for RDX was not met by this ISCO demonstration.
Ease of use	Implementation of ISCO/ERI will complement each other in determining permanganate location and RDX destruction rates.	ERI did assist in locating permanganate behavior, but quantification of varying permanganate concentrations by ERI was not achieved.

Table 5. Project performance confirmation (continued).

Primary Criteria	Expected Performance Metric (pre demo)	Actual Performance
PRIMARY CRITERIA (Performance Objectives) (Quantitative)		
Target contaminant - % Reduction - Regulatory standard	 RDX removal by 97% Achieve USEPA's HA concentration (2 µg/L) for RDX	 Achieved between 70 and 80% reduction in RDX concentrations. Not met
Hazardous materials	None	Degradation products of RDX not detected by liquid chromatography/mass spectrometry (LC/MS) using Cassada et al., 1999
Process waste	Well cuttings and purge water	Taken to treatment facility
Factors affecting performance - Throughput - Media size - Media constituents	 Not a concern, as most of the time for injection and sampling is fixed. NOP aquifer material is sandy. Media constituents will not affect ISCO/ERI process, as the permanganate is soluble in water and has no affinity for sorption.	 Groundwater sampling of permanganate influenced wells was achieved within 3 to 4 hours. ERI measurements will yield spatial distribution (2-D) of permanganate plume. This 2-D image will verify how well permanganate was injected. Analysis of permanganate concentrations from monitoring wells using UV detection.
SECONDARY PERFORMANCE CRITERIA (Qualitative)		
Plume size	RDX size in demonstration area will get smaller. Permanganate plume size will dissipate and decrease in concentration as it moves down gradient.	70 to 80% reduction in RDX concentration ERI was mainly effective in identifying permanganate distribution right after injection.
Reliability	No breakdowns	Record keeping
Safety - Hazards - Protective clothing	 Oxidants Modified Level D personal protective equipment (PPE)	 Experience from demonstration operation
Versatility - Intermittent operation - Other applications	 No, oxidant will be added only once. ISCO/ERI process can be applied to any explosives contaminant aquifer with slight modifications on quantity and frequency of amendment addition.	 The ERI characteristics of site needed for future use of ERI with permanganate have been identified.

Table 5. Project performance confirmation (continued).

Primary Criteria	Expected Performance Metric (pre demo)	Actual Performance
Maintenance Required	None, except for pump or other equipment breakdown	Experience from demonstration operation
Scale-Up Constraints		
- Engineering	None, only more wells may be needed depending on plume shape and size	Monitor during demonstration operation
- Flow rate	Flow rate will control time frame needed for permanganate injection	Experience from demonstration operation
- Contaminant concentration	Not a concern	Experience from demonstration operation

4.3 DATA ASSESSMENT

If multiple datasets are collected at different times from the same locations, resistivity differencing can be employed. Resistivity differencing is more sensitive to variations in the subsurface than standard ERI surveys. Because standard ERI surveys collect data that detects properties of the subsurface's sediments and fluids at the same time, resistivity differencing can be used to evaluate isolated changes that are independent of sediment properties.

4.4 TECHNOLOGY COMPARISON

Historical methods of site assessment relied primarily on two detection and monitoring strategies, both of which relied on multiple boreholes. The first strategy involves discrete point sampling of fluids drawn from wells or multilevel piezometers whose data are interpreted by hydrogeologists, civil engineers, and other scientists. The second strategy uses indirect measurements through surface or borehole geophysical techniques.

The difficulties with point sampling are the cost and time of drilling and sample collection, analysis, and interpretation time. Further, point sampling methods typically provide low data density and thus miss contaminants transported on flow paths or stored in clay lenses not sampled by wells. This is especially problematic if the contaminants are moving non-uniformly such as density-driven fingering or in isolated flow paths in heterogeneous media. In some settings, the very act of probing and monitoring the aquifer can create additional heterogeneity and new preferential flow paths for solutes. Attempts to improve data quality by increasing data density requires additional boreholes, increasing already high initial costs.

ERI provides more complete and more economical data coverage than borehole-dependent methods. A temporary, surficial ERI system can be used to evaluate a 2-D or 3-D portion of the subsurface; the resulting ERI images can then be used to choose specific targets for traditional investigation methods. ERI systems can support long-term monitoring with the installation of cables in boreholes or shallow trenches.

Comparing ERI assessment with direct push is also difficult as they are not a direct comparison. The common case is to employ ERI when either wells or direct push methods fail to provide data that allows the site data to be well understood. In this case, the ERI data that is collected is an additional cost that then needs confirmation from further direct push work. This is generally due to the ERI data providing narrow targets of investigation that were missed in previous data collection periods.

If collected during the initial site characterization, ERI data allows direct push evaluation to be highly targeted toward providing a correlation with the ERI dataset. This is similar to the petroleum and mining industries use of seismic datasets. A “Common Earth” approach is employed to evaluate difference between the data types, as contradictory data will exist between the ERI and the direct push data. Generally, this approach lowers the overall cost of direct push data collection but increases the overall cost of site characterization.

This page left blank intentionally.

5.0 COST ASSESSMENT

5.1 COST REPORTING

Although not directly related to the ERI technology, costs associated with the pilot-scale ISCO demonstrations are presented in Table 5.

Table 6. Cost reporting—environmental restoration remediation technology.

COST CATEGORY	Subcategory	Costs ($)
FIXED COSTS		
	Contractor	Aquifer Solutions Contractor Costs Equipment rental subsurface injection $5,260 Injection Activity MOB/DEMOB* $8,100 Material and Supplies $3,081 Contingency fee $822
	Planning/Preparation	$4,000
	Equipment Instrument cost (if purchased) Other equipment	Variable frequency drive controller $509 Water pump $2,452 Portable spectrophotometer $2,653
	Other Monitoring well installation	$6,500
	Subtotal	**$33,377**
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Labor (including any sampling required and travel)	$5,000
	Materials/consumables	Permanganate $9,958 Consumables $1000 Groundwater analyses (mass spec method) $15000
	Utilities/fuel	Diesel and gasoline $150
	Instrument cost (if rental or lease)	$660 pump + $660 generator
	Sub-Total ($)	**$32,428**
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Disposal of residues/well-water, well cuttings	$830
	Subtotal	**$830**
TOTAL COSTS		
	TOTAL TECHNOLOGY COST	**$66,635**

*MOB/DEMOB = mobilization/demobilization

The costs for ERI site characterization are summarized in Table 6 and separated into capital costs, operation and maintenance, and other technology-specific costs. Basic costs and the variations depending on site characteristics are described below.

Table 7. Cost reporting—environmental restoration site characterization technology

Cost Category	Subcategory	Costs ($)
FIXED COSTS		
1. CAPITAL COSTS	Mobilization/demobilization	$7,000 U.S. MOB/DEMOB ($20,000 International)
	Planning/preparation	$4,000
	Equipment Instrument cost (if purchased) Other equipment	$50,000 $50,000
	Other Management support	$5,000
	Subtotal	$60,000
VARIABLE COSTS		
2. OPERATION AND MAINTENANCE	Labor (including any sampling required and travel)	$5,500/day
	Materials/consumables	$100/day
	Utilities/fuel	$50/day
	Instrument cost (if rental or lease)	$315/day + $250 equipment prep
	Subtotal	$3915/day
3. OTHER TECHNOLOGY-SPECIFIC COSTS	Disposal of residues/well-water	N/A
	Data visualization and reporting	$1500/field day
	Subtotal	$2500
	TOTAL TECHNOLOGY COST	$53,377
	Throughput achieved	44 ERI lines with ~1600 model data
	Unit cost per sample	$0.76/sample

The costs for ERI subsurface imaging are summarized in Table 8 and are discussed below. These costs are separated between the Background Data Collection Phase and the Injection Monitoring Phase. The typical baseline costs and cost variations depending on site characteristics are also summarized in the below sections of this report and Table 8.

5.1.1 ERI Background Data Collection Phase Costs

The background data collection phase allows the collection of the initial set of ERI data to obtain baseline pre-injection subsurface images and to allow the installation of electrodes on the site for monitoring the injection period. The costs for site mobilization involve the preparation of equipment and preparing the equipment for shipping. If the work is performed near an existing equipment location, the ERI equipment is loaded into a trailer and hauled to a work site. If the site is remote or overseas, the equipment is palletized and shipped via a freight service via either truck or air.

Roundtrip mobilization/demobilization costs are typically in the range of $7,000 including transportation of personnel and equipment to/from the project site. For international work (i.e.,

outside the U.S) with additional transport and insurance costs, the mobilization/demobilization costs can increase up to approximately $20,000.

The project planning and preparation generally involves a planning of the number and orientation of transect lines and the number of intervals to be imaged. This allows the data to be collected as efficiently as possible by integrating site data from a project site with experience at collecting useful images. The project planning phase also generally includes the preparation of a project plan in the form of a proposal or a quality assurance project plan (QAPP.) If a formal work plan or QAPP is required, this effort generally costs approximately $4,000, and can increase with increased reporting and planning requirements.

The costs for monitoring an injection are based on installing a set of electrodes at the site and connecting geophysical cables with electrode “take-outs” to the electrode stakes during each monitoring period. If the decision is made to deploy a dedicated set of geophysical cables for the duration of an injection monitoring period, the capital costs increase in buying a set of cables that are semi-permanently deployed. This type of deployment will also require the use of a trenching machine to insert the cable into the subsurface depending on site requirements. The advantages to this semi-permanent installation include the following:

- Decreases the number of personnel required to acquire additional sets of ERI data should they be desired over a longer monitoring period (i.e., greater than one week) as the operator only needs to plug into the system. This provides a cost savings for additional monitoring events using ERI.

- The need for electrode stakes is eliminated because the buried electrodes have direct contact with the soil beneath the ground surface.

A budgetary costs for this type of initial installation is estimated at $60,000 and will vary depending on the configuration and site conditions. If the site were remote or were to be sampled often, an instrument could be deployed onsite with a satellite link providing the ability to continuously monitor the site in an unmanned configuration. This approach would reduce labor and travel costs and would add the cost of a dedicated instrument and cellular or satellite connection to the system costs.

The field work is based on the assumption of 6 ERI transect lines monitoring a single injection point with 3 transect lines in orthogonal directions. Costs for ERI data acquisition typically average $5,500 per field day includes budget for a crew of three people (plus equipment and travel costs) who are deploying electrodes and cables, running the instrument, and land surveying the geophysical survey transect line locations. Adding additional personnel doesn’t generally increase the speed for acquisition unless the transect lines are long (i.e., greater than ~200 m). For longer transect lines, land survey work may be required in advance to assist in planning the data acquisition and obtaining buried utility markouts. As discussed above, the per field day or per survey costs are reduced when using semi-permanently installed electrodes, because a single person can attached the instrument to the cables and collect data. If a permanent instrument is deployed, a single person can remotely access the instrument to collect and transmit ERI survey data.

Once the ERI geophysical data are collected, they are processed in conjunction with the topographic land survey data to obtain topographic corrections. ERI data becomes much more valuable when the data are evaluated in three or four dimensions (i.e., 3-D or 4-D; 4D is 3-D data viewed over time) and compared against existing soil boring and/monitoring well data.

The visualization of the data requires a conversion from two dimensional (2-D) vertical “slice” images to three dimensional coordinates and then preparing additional data for visualization. This effort increases with an increased amount of data and can be estimated at a cost of $750 per field day. A report is written to allow evaluation of the site conceptual model and to evaluate the injection planning. This effort can be estimated at $750 per field day.

5.1.2 ERI Injection Monitoring Phase Costs

The costs for monitoring an injection is based on assuming that electrodes for 6 transect lines of 56 electrodes were installed in the background data phase. The field work consists of monitoring hydraulic changes due to the injection system being run with fluid, but without injectate. Then two sets of additional data are collected after the injection to monitor the flow of injectate.

Labor costs for ERI data acquisition run $5,500 per day. This is for a crew of three people who are deploying cables to existing electrode locations and running the instrument. Adding additional personnel doesn’t generally increase the speed for acquisition unless the transect lines are long (>200 m). Labor costs decrease for semipermanently installed electrodes if cables are installed. A single person can attached the instrument to the cables and collect data. If a permanent instrument is deployed, a single person can remotely access the data.

Once the data are collected, they are processed using the topographic survey and geophysical datasets. As more than one dataset exists for each transect line, each dataset can be differenced against the previous dataset to evaluate the changes in the subsurface. ERI data becomes much more valuable when the data are evaluated in three or four dimensions and compared against existing core or well data. The visualization of the data requires a conversion from two dimensional slices to three dimensional coordinates and then preparing additional data for visualization. This effort increases with an increased amount of data and can be estimated at a cost of $750 per field day. A report is written to evaluate the distribution of injectate and to revise the site conceptual model if necessary. This effort can be estimated at $750 per field day.

Table 8. Cost Estimating — Environmental Restoration Site Characterization using ERI Technology

Cost Category	Sub Category	Budgetary Costs ($)	
1. BACKGROUND DATA COLLECTION PHASE (For general site characterization and injection planning)	Mobilization/demobilization	$7,000 U.S. ($20,000 Intl.) Lump Sum per Occurrence	$7,000
	Project Planning/Work Plan or QAPP Development	$4,000	$4,000
Assuming 6 monitoring transect lines of 56 electrodes	Monitoring electrodes installed cost	$10,000 Lump Sum	$10,000
	ERI Field Work	5 field days @$5,500	$16,500
	Data Processing	5 field days @$500	$1,500
	Visualization	5 field days @$750	$2,250
	Reporting	5 field days @$750	$2,250
Sub-Total ($)		**Background Data Collection Phase**	**$43,500**
2. INJECTION PERIOD MONITORING (For delineating 4-D distribution of injectate)	Mobilization/demobilization	$7,000 U.S. ($20,000 Intl.)	$7,000
Assuming 3 monitoring periods	ERI Field Work	$5,500/day	$27,500
	Data Processing	$500/day	$2,500
	Visualization	$750/day	$3,750
	Reporting	$750/day	$3,750
	Sub-Total ($)	**Injection Monitoring Phase**	**$44,500**
TOTAL COSTS			
TOTAL TECHNOLOGY COST ($)			**$88,000**
Throughput Achieved			24 ERI images (+ 18 differenced images)
Unit Cost per ERI Survey Image (i.e., per “Sample” Cost) ($)			**$3,660/image**

5.1.3 ERI Technology Specific Cost Drivers

For ERI characterization and monitoring, the cost drivers are defined by the site conditions and the overall objectives. Each driver is discussed separately.

Mobilization: The ERI equipment can be palletized and shipped worldwide. If the location is accessible by truck, additional equipment can be mobilized to the site for traffic control or other contingencies.

Monitoring Periods: For transient analysis of ERI data, the number of monitoring periods define what type of equipment can be cost effectively employed. The costs decrease with an increasing number of periods as permanent cables can be installed in the shallow subsurface instead of repeatedly installing cables at the surface. Additionally, if a site is to be monitored for a large

number of monitoring periods, a dedicated system can be installed for the life of the project that can be monitored remotely.

Traffic Control: Costs increase if a site requires traffic control. This can be achieved through overnight surveying, traffic controls and lighted barricades, and traffic rated cable ramps. These factors primarily increase the time to deploy geophysical cables to achieve project objectives and are normally not a significant cost at typical injection sites.

Ground Surface Characteristics: Vacant grass fields with soft soil allow faster and cheaper ERI data acquisition than more complex urban environments, concrete pavements, or thick vegetation. In concrete areas, to avoid data ambiguity and increase data quality, 1/2 inch diameter holes are drilled to allow the 3/8 inch diameter electrodes to contact native soil. If the concrete must remain intact, conductive gels can be employed to collectively couple to the surface of the concrete and collect data.

The ERI techniques discussed in this report have been employed in environments ranging from jungle floors to oil refinery complexes. The technique can be used across water and solid rock. The cost is defined by the rate of data collection and which site specific factors slow the acquisition of data.

Survey Line Length: For surface only ERI surveys, the total transect line length affects the time for acquisition. Generally, for 3 meter spacings on a 56 electrode survey (165 meters total length), four transect lines of data can be collected per day. For longer transect lines, the number of lines decrease to 1-2 per day as the distance becomes more labor and time intensive to manage.

Survey Resolution: In urban environments or for monitoring injections, additional time is required for data collection to achieve a higher resolution data set. This decreases the number of transect lines possible per day.

Number of Correlation Sites: Data correlation with ERI datasets generally results in a large portion of the ERI geophysical data correlating strongly with other datasets such as soil boring or monitoring well data. There are almost always discrepancies due to well mixing processes, long screened intervals causing averaging, data collected at much different times, and other causes. As the size and complexity of the datasets increase, so does the time and cost of correlating these datasets.

Data Visualization Requirements: Visualization of datasets is a time consuming process. All datasets must be converted to x, y, z, t (i.e., geospatial and time) coordinates which is somewhat time consuming for ERI datasets, but is generally much more time consuming for archival well and boring datasets for comparison. If a well-maintained and complete site database exists, visualization can be quite rapid, but this is not often the case relative to spatial and temporal coordinates for historical data sets.

5.2 ERI COST COMPARISON

For ERI analysis, the comparison is not as simple as it is often compared against monitoring wells alone. It could also be compared against direct push electrical conductivity logging. For

this project the ERI costs involve equipment, labor, travel, data processing, data visualization, and reporting.

The equipment and labor can generate approximately four transect lines of data per day. Commercially, this is performed at a cost between $2000 to $4000 per survey image including reporting. If additional visualization is performed (e.g., solid 3-D model), additional charges of $2000 to $5000 are incurred depending on the amount of visualization required. If additional correlations and analysis are performed, other than posting well locations and concentration data, additional time is involved with additional costs. For this project, there were 13 field data collection days and a 3D visualization performed. This would cost approximately $84,500 plus visualization and analysis.

These costs were compared against standard monitoring wells. To collect a comparable number and distribution of data would require approximately 204 wells or boreholes spaced every 10 meters in the core data area to a depth of 30 m (98 ft). At an assumed cost of $3,500 per hole, the well installation would cost $714,000 before sampling. This would not include the examination for the deeper aquifer portions, nor multilevel wells to obtain vertical data. If the larger areas evaluated were included, the costs would be much higher.

However, ERI cannot be performed to quantitatively assess hydrogeology without using wells. The well placement can be greatly improved by focusing on areas of high and low hydraulic conductivity in this case and provide samples that demonstrate the range of possible values in the subsurface. Once this process has been performed, the ERI tool can be used to scan other locations and provide similar information without needing the large number of monitoring points required.

This page left blank intentionally.

6.0 IMPLEMENTATION ISSUES

6.1 COST OBSERVATIONS

For ERI data collection, much of the costs over time are due to labor. If a monitoring system is installed to track changes over numerous periods or significant amounts of time, electrodes can be permanently installed to limit labor costs. The system can either be operated remotely or have a single technician collect data from a port in the field.

6.2 PERFORMANCE OBSERVATIONS

The ERI did not provide the results that were expected. This is due to site conditions affecting the transport velocity of the injectate and the weak overall signal due to suppression. A protocol of evaluating results of pumping alone or injecting electrical tracer to determine signal strength due to injectate changes could save time and improve the estimate of sampling period times.

6.3 SCALE-UP

Scaling ERI data collection up to longer time periods or larger areas does not require significantly different protocols. If the scale is large enough, permanent electrode installation may be warranted. If significantly greater depth is required (greater than 100 m (300 ft)), labor costs increase due to logistical considerations.

6.4 OTHER SIGNIFICANT OBSERVATIONS

The direct push sampling (see the Final Report) showed that following injection, the permanganate followed the natural flow paths taken by the RDX. This was evident by the modest correlation observed between finding permanganate and RDX together in discrete zones (or fingers) and not detecting RDX in zones where no permanganate was found. Low permeable zones have been known to act as sinks for chlorinated contaminants like TCE, but in the case of RDX, this more soluble compound appears to remain in the more conductive zones. We believe that this bifurcation or plume fingering was due to preferential pathways caused by the depositional nature of the Todd Valley sands, which were deposited in a braided stream system similar to the current Platte River near Ashland, NE. The sedimentology of a braided stream is complex and encompasses several channels characterized by high width/depth ratios. Because of this stratification, monitoring wells only captured fingers of permanganate that was mixed with non-treated groundwater during pumping, thereby diluting permanganate/bromide concentrations within the well and artificially inflating RDX concentrations due to mixing within the well casing. Despite problems encountered in getting the permanganate curtain uniformly distributed and throughout the well screen interval, the observed RDX destruction rates from this pilot-scale demonstration provide proof-of-concept that permanganate can degrade RDX in situ and support permanganate as a possible remedial treatment for the RDX-contaminated groundwater.

6.5 LESSONS LEARNED

Even with an improved ERI technique, monitoring injections is inherently difficult. An experiment should anticipate weak signal and plan for accelerated velocity of injectate and unexpected direction of migration. This could be accomplished by installing permanent

electrodes that can be used during the entire monitoring phase. This was not possible at this site, as a portion of the site was being used for agronomic activities that required machinery access to the fields. In addition, background ERI measurements were made during stagnant, non-pumping times. By taking ERI measurements during actual groundwater recirculation, with and without the permanganate addition, a closer resolution of differences in signals (before and after permanganate addition) may have been obtained.

For future monitoring experiments, several protocol modifications can be made to improve results. The modifications are listed first as modifications to the ERI approach. Secondly, modifications to the injection and well sampling protocols are listed.

ERI Modifications:

1. Semipermanent electrodes can be installed at the surface for the duration of the experiment. While this will not improve the results dramatically, it can provide an increase in signal-to-noise ratio that can be important. This would have been difficult at the Mead site as part of the site was being actively farmed for soybeans, another for corn, and the remainder was actively mowed to limit the height of grasses. This can either be performed by installing graphite rods and attaching cables to them during each interval, or installing cables in shallow trenches below the depth of surface activities. If this approach is used somewhat regularly, having semipermanent cables installed would be the more cost-effective option.

2. All ERI monitoring should be done assuming that transient data will be the only source of monitoring data. The assumption with the experiment was that data in the resistivity domain would allow a calibration to the injection fluid. However, the most sensitive data is obtained in the transient ERI mode and should be assumed to allow the most rapid ability to modify protocols in the event that the injection is very different from the proposed injection plan.

3. Imaging for only fluid movement should be included at the same flow rates and locations as the planned injection prior to injection of permanganate or other compounds. This was not possible with this experiment as it was designed to amend an already existing experiment. By monitoring a test of the injection system with only water and tracer, vadose zone and conservative tracer changes can be separated from the injectate signals. This can be done with or without electrical tracers such as chloride or bromide solutions, depending on the setting.

Injection Modifications:

1. Assume that the injectate will primarily move up into the vadose zone. This was observed during this experiment and at two additional commercial sites using this technique. If the material is to be delivered to the phreatic zone only, injection rates and monitoring should be adjusted to catch vertically upward movement of injectate.

2. Any monitoring system should include smaller piezometers screen lengths to ensure that less fluid mixing occurs in the samples for geophysical calibration. This is often difficult as injections are often performed on preexisting sites, but if smaller screens are an option, they should be installed based on the property distribution defined by ERI data.

3. Injection curtains should be established at lower pumping rates to control fingering. The lower head changes in the aquifer will increase injection costs by increasing delivery times but will likely improve delivery to the zones of interest.

4. Vertical gradients near injection zones need to be established to assist in predicting the movement of injectate. If piezometers are available to determine vertical gradients, they can also be used during injection to determine if significant vertical movement is occurring.

6.6 END-USER ISSUES

At sites where munitions were manufactured or assembled, soil contamination has typically resulted from the once common practice of releasing explosive-tainted wastewater to drainage ditches, sumps, settling ponds, or impoundments. TNT manufacturing, for example, required large volumes of water for purification. The aqueous waste produced from this process, known as red water, has been found to contain up to 30 additional compounds besides TNT (Urbanski, 1984). Similar practices occurred at loading, packing, and assembling plants, where wastewater (also known as pink water) generated during plant operations was routinely discarded outside into sumps and drainage ditches. Left untreated, surface soils laden with wastewater constituents eventually became point sources of ground water contamination. One study showed that of the numerous sites sampled, >95% contained TNT and 87% exceeded permissible groundwater concentrations (Walsh et al., 1993).

The primary end user for this innovative in situ technology will include federal ordnance sites with explosive-contaminated groundwater plumes. Currently there are 583 sites with confirmed explosive-contaminated groundwater at 82 installations nationwide. At 22 other installations, 88 additional sites are suspected of groundwater contamination with explosives and organics (DENIX, 2003).

6.7 APPROACH TO REGULATORY COMPLIANCE AND ACCEPTANCE

The acceptance of any geophysical technique will require time for the field to accept the use of a scanning tool. Previous experience from the medical profession and the petroleum industries indicates that adoption of a scanning tool takes a significant amount of time and effort. Both other industries accept the extra costs of scanning their systems (patients or reservoirs) in order to make better technical judgments. As the environmental industry becomes more results driven, a tool to monitor and confirm subsurface activities will become standardized to meet the newer technical requirements.

This page left blank intentionally.

7.0 REFERENCES

Cassada, D.A., S.J. Monson, D.D. Snow, and R.F. Spalding. 1999. Sensitive determination of RDX, nitroso-RDX metabolites, and other munitions in ground water by solid-phase extraction and isotope dilution liquid chromatography-atmospheric pressure electro-spray ionization mass spectrometry. J. Chromatog. A, 844:87-95.

Condra, G. E., E.C. Reed. 1943. The geological section of Nebraska. Nebraska Geol. Survey Bull. 14, 82.

Defense Environmental Network and Information Exchange (DENIX). 2003. Enhanced alternative and in situ treatment technologies for explosives in groundwater. URL: http://www.denix.osd.mil/denix/DOD/Policy/Army/Aerta/Report/a12a.html.

Halihan, T., and T. Fenstemaker. 2004. Proprietary Electrical Resitivity Imaging Method. 2.0 ed. Oklahoma State University Office of Intellectual Property, Stillwater, OK.

Halihan, T., S. Paxton, I. Graham, T. Fenstemaker, and M. Riley. 2005. Post-Remediation Evaluation of a LNAPL Site Using Electrical Resistivity Imaging. Journal of Environmental Monitoring, v 7, p. 283-287. DOI: 10.1039/b416484a.

Hundal, L.S., J. Singh, E.L. Bier, P.J. Shea, S.D. Comfort, and W.L. Powers. 1997. Removal of TNT and RDX from water and soil using iron metal. Environ. Pollut. 97(1-2):55-64.

Nyquist, J.E., B.J. Carr, and R.K. Davis. 1999, DC Resistivity Monitoring of Potassium Permanganate Injected to Oxidize TCE In Situ. Journal of Environmental and Engineering Geophysics, v. 4, p. 135-147.

Piskin, R. 1971. Hydrogeology of the University of Nebraska field laboratory at Mead, Nebraska. University of Nebraska PhD Dissertation.

Sima, A.M., T. Halihan, K. Thompson, G. Fox, and D. Storm. 2008. Transient Electrical Resistivity Imaging of a Tracer Test, Tahlequah, OK. GSA South-Central Sectional Meeting, Hot Springs, AK, April 2008. Geological Society of America Abstracts with Programs, Vol. 40, No. 3, p. 7.

Stollar, R.L., and P. Roux. 1975. Earth resistivity surveys—a. method for defining ground-water contamination. Ground Water 13:145-150.

Urbanski, T. 1984. Chemistry and technology of explosives. Pergamon Press, Oxford.

USACE. 2007. The former Nebraska ordnance plant, Mead, NE. Site background and information available at http://www.nwk.usace.army.mil/projects /mead/ Site_Information_and_Background/NOP_Fact_Sheet.pdf. U.S. Army Corps of Engineers, Kansas City, MO.

Van Nostrand, R.G., and K.L. Cook. 1966. Interpretation of Resistivity Data. U.S. Geological Survey Professional Paper 499. 310pp.

Walsh, M.E., T.F. Jenkins, P.S. Schnitker, J.W. Elwell, and M.H. Stutz. 1993. USA Cold Regions Research and Engineering Laboratory CRREL Special Report 93-5, pp. 1-17. Hanover, NH.

Webb, G., S.W. Tyler, J. Collord, D. Van Zyl, T. Halihan, J. Turrentine, and T. Fenstemaker. In press. Field Scale Analysis of Flow Mechanisms in Highly Heterogeneous Mining Media. Vadose Zone Journal.

Woodward-Clyde. 1995. Engineering evaluation/cost analysis for operable unit No. 2 (groundwater) former Nebraska Ordnance Plant, Mead, Nebraska DACA 41-92-C-0023. Prepared for the Department of the Army, U.S. Army Engineers District, Kansas City District, Corps of Engineers, Kansas City, MO, May, 1995.

APPENDIX A

POINTS OF CONTACT

Point of Contact Name	Organization	Phone Fax E-Mail	Role
Steve Comfort	School of Natural Resources University of Nebraska 256 Keim Hall Lincoln, NE 68583-0915	402-472-1502 402-472-7904 scomfort@unl.edu	Principal Investigator (PI)
Todd Halihan	School of Geology Oklahoma State University 105 Noble Research Center Stillwater, OK	405-744-6358 405-744-7841 todd.halihan@okstate.edu	Co-PI
Vitaly Zlotnik	Geosciences University of Nebraska 318 Bessey Hall Lincoln, NE 68502-0340	402-472-2495 402-472-4917 vzlotnik1@unl.edu	Co-PI
Mark Burbach	School of Natural Resources University of Nebraska 512 Hardin Hall Lincoln, NE 68583-0995	402-472-8210 402-472-2946 mburbach@unl.edu	Co-PI
Jeff Albano	School of Natural Resources University of Nebraska 255Keim Hall Lincoln, NE 68583-0915	402-730-9170 402-472-7904 albanoj@gmail.com	Graduate Student
Chanat Chokejaroenrat	School of Natural Resources University of Nebraska 255 Keim Hall Lincoln, NE 68583-0915	402-326-8661 402-472-7904 chanatunl@gmail.com	Graduate Student
Wilson Clayton	Aquifer Solutions, Inc. 29025A Upper Bear Creek Rd. Evergreen, CO 80439	303-679-3143 ext#11 303-679-3269 wclayton@ aquifersolutions.com	Contractor
Bruce Marvin	Aquifer Solutions, Inc. 950 Gilman Street, Suite 101B Berkeley, California 94710-1462	510-525-4440 ext#1 510-525-4474 bmarvin@ aquifersolutions.com	Contractor
Andrea Leeson	ESTCP Office 900 N. Stuart Street Suite 303 Arlington, VA 22203	703-696-2118 703-696-2114 Andrea.leeson@osd.mil	Environmental Restoration Program Manager

ESTCP Program Office

901 North Stuart Street
Suite 303
Arlington, Virginia 22203

(703) 696-2117 (Phone)
(703) 696-2114 (Fax)

E-mail: estcp@estcp.org
www.estcp.org